NASA TECHNICAL MEMORANDUM NASA TM-75442

THE STIRLING ENGINE FOR VEHICLE PROPULSION

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(NASA-TM-75442) THE STIRLING ENGINE FOR VEHICLE PROPULSION (National Aeronautics and Space Administration) 14 p HC A02/MF A01 CSCL 10A

N79-12547

Unclas G3/44 38010

Translation of "Der Stirlingmotor als Fahrzeugantrieb." VDI-Berichte, No. 224, 1974, pp. 87-91

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546 NOVEMBER 1978

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1. Introduction

The requirements for protection of the environment launched /87 the discussions of alternate means of propulsion several years ago; the energy crisis has added some new aspects to these discussions. One of the most interesting alternate means of propulsion is the Stirling motor whose characteristics and present state of development--in particular with respect to its use for vehicle propulsion--will be related below.

2. Characteristics

The characteristics of the Stirling engine will be described as they are found on present experimental motors, to allow some judgment about the possibilities of its use. It must be kept in mind, of course, that improved data are to be expected by the time of its later application.

2.1 Power output data

Fig. 1 shows the torque of a 4-cylinder Stirling engine with 85 kW (about 120 PS) against revolutions with the mean cycle pressure serving as parameter. The mean cycle pressure is the average value per time unit of the working gas pressure in the cylinder and is a measure for the engine load. A torque increase at lower rpm is to be noted, but is not very high in this case. A steeper torque increase could be achieved--for a vehicle motor for instance--through changes in design.

In Fig. 2 the efficiency of the same engine is plotted, also as a function of rpm and average cycle pressure. The highest efficiency of about 33% occurs at the highest load and at average rpm. Particularly important for vehicular use are the efficiencies, which are favorable even for partial loads over the entire rpm range, leading to low fuel consumption for mixed load operations.

2.2 Composition of exhaust gases

One of the most important arguments for the use of the Stirling engine in motor vehicles is its clean exhaust gas. Figs. 3 and 5 show test results from an experimental motor that operated without recycling of the exhaust gas. Emission of CO and HC is extremely low and far beneath all expected requirements. Because of the high combustion temperatures NO_x emission values are not so favorable but are still at such a low level that 5 g/PSH for the sum of NO_x and HC are not exceeded in the 13-step cycle. Investigations by Philips have shown that even the previous limit of 0.4 g/mile in the CVS-test can be reduced by recycling of exhaust gases. It is finally worth noting that the exhaust from the Stirling engine is free of soot and odors. /88

2.3 Noise

In addition to the clean exhaust gas the Stirling engine also shows another characteristic favorable to the environment, very low noise generation. Fig. 6 shows the acoustic pressure levels for various rpm and loads, as measured on a one-cylinder engine with 22 kW (30 PS), at 1 m distance. The value of 85 db(A) at rated load is very low, i.e., the Stirling engine is not only much quieter than a Diesel engine but also quieter than an Otto engine.

2.4 Volume and weight

In comparison to internal combustion motors, the external combustion system and the heat exchangers of the Stirling engine require more room and increase the weight. On the other hand, mean effective pressure and power output per liter (output/stroke volume) are decidedly higher for the Stirling engine than for internal combustion motors. The mean effective pressure of Stirling engines is today at around 25 bar, with work being done for each engine turnover--as in the two-cycle motor. Forecasts about the dimensions of future Stirling engines are not immediately possible since the present experimental motors are still pretty big and not yet optimized in their volume and weight. It can safely be assumed that with progressive improvements in design and increase of power output through increase of internal pressure, weight per kW will be cut in half for future engines, reaching values below 4.5 kh/PS, resp. 6 kg/kW. These data are for engines using helium as working gas while concentration of output can be much more increased by switching over to hydrogen.

2.5 Controllability

As with all engines requiring external heat supply, more control apparatus is required for the Stirling engine than for an internal combustion engine. On the one hand, the output of /89
the Stirling engine must be controlled by intervention in the thermodynamic process (output control); on the other hand, the heat generation, i.e., fuel and air supply, must be adapted to the engine output (temperature control).

Temperature control presents no basic difficulties. Fuel and air supply for the experimental motors are controlled by a thermo-element and an amplifier so that the temperature of the

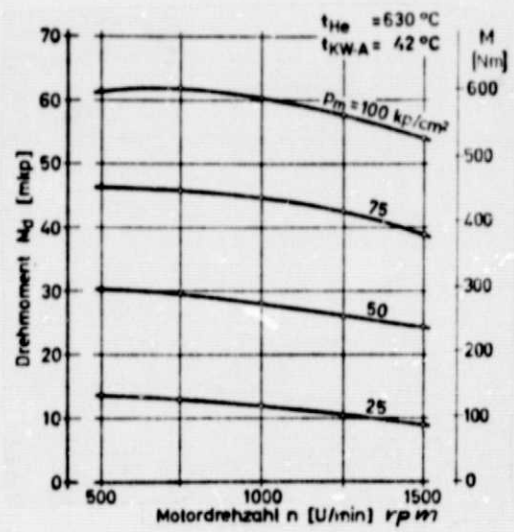

Fig. 1 Torque curves of a 4-cylinder Stirling engine for various mean cycle pressures.

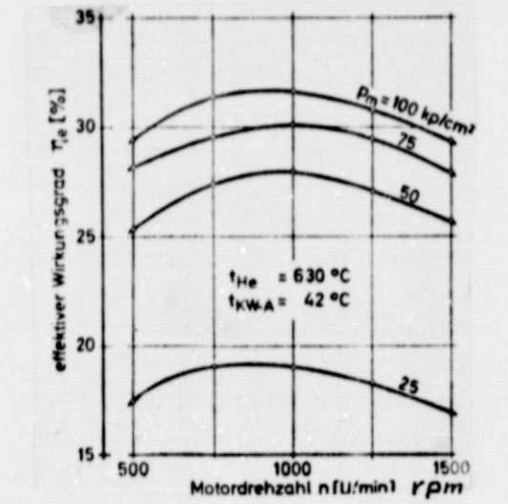

Fig. 2 Efficiency of a 4-cylinder Stirling engine for various mean cycle pressures.

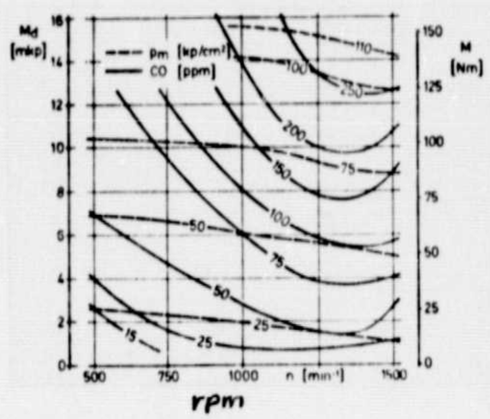

Fig. 3 CO-emission of a one-cylinder Stirling engine.

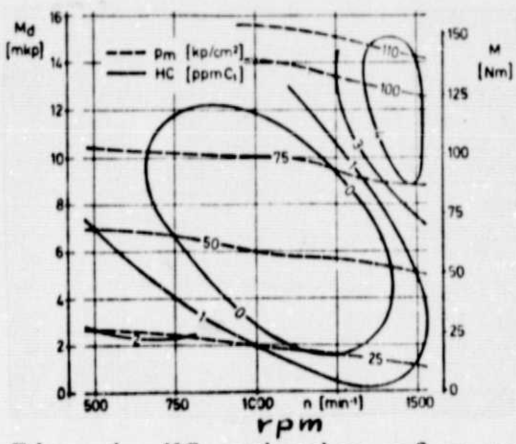

Fig. 4 HC-emission of a one-cylinder Stirling engine.

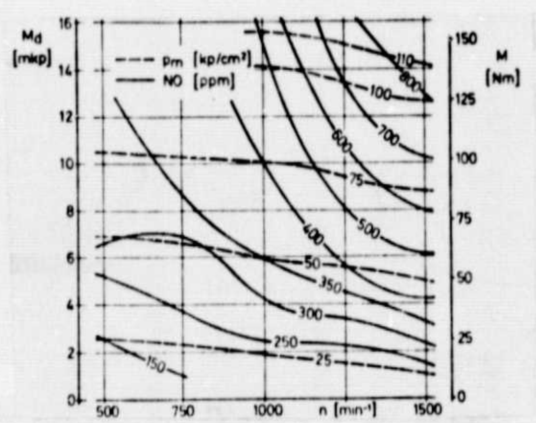

Fig. 5 NO-emission of a one-cylinder Stirling engine.

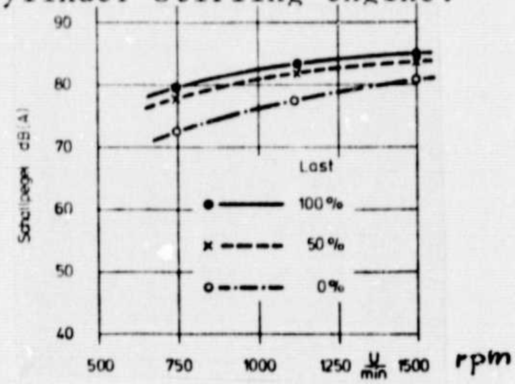

Fig. 6 Acoustic pressure levels measured at 1 m distance from a one-cylinder Stirling engine.

working gas in the heater of the Stirling engine remains equally high for all load conditions. In principle it is possible to use simpler temperature controls but they were not developed. Various systems are presently used for output control, each showing advantages and disadvantages.

When using pressure control the mean pressure of the working gas in the cylinder is varied by the introduction or the pumping out of working gas (helium). This type of control shows the best efficiencies for partial loads, but the pumping out requires a certain amount of time on the order of several seconds, depending on the size of the compressor.

Short-circuit control, where top and bottom faces of the working cylinder are connected with each other through a valve, reacts without loss of time but causes high losses, i.e., low efficiencies at partial loads.

For damaged-space control, additional spaces, also filled with working gas, are connected to the cylinder volume through valves, which causes a drop in the output. This control also works practically without time delay, efficiencies for partial loads are not as good as with pressure control but better than for short-circuit control.

According to the application, the above methods can be combined for output control. The toughest requirements are for the operation of vehicles in city traffic where there are very frequent load changes and a requirement for brief response times. It is possible to meet these requirements today but a lot of development work must still be done for optimization of the output control towards lower fuel consumption.

2.6 Starting procedure

To start the Stirling engine a fuel pump and burner air-compressor are actuated by a small electric motor. The burner is ignited by a spark plug from a briefly turned on ignition system, bringing the heater of the Stirling engine subsequently to the operating temperature. The engine is then turned over by a starter and continues to run immediately on its own. As soon as the break in the heater temperature, which occurs during startup, is compensated for the engine can accept full load. The entire starting procedure takes 30-60 secs.

2.7 Multifuel capability

The Stirling motor is known for its characteristic to operate with practically all liquid and gaseous fuels. This multifuel capability was also demonstrated with a whole series of fuels on experimental motors. Because of the continuous, external, combustion employed in the Stirling engine no requirements as to octane number or cetane number are made of the fuel. Beyond that technical combustion data like the heating power of the fuel or the air ratio have no influence on the engine output.

3. Required Further Developments

The characteristics of the Stirling engine listed in section 2 show that it is entirely suitable for vehicle propulsion. Particularly positive are its environmental characteristics and its modest requirements regarding fuel characteristics, while weight and volume must still be reduced through further development.

Technically, the use of the Stirling engine for vehicles is feasible--though a few problems still have to be solved. The

cost effectiveness of a vehicle driven by a Stirling engine, as compared to our present drives, will be decisive.

Operating costs are mainly determined by the efficiency of the propelling machine. For that reason costs for the Stirling /90
engine will be lower than for the Otto engine, resp. higher than for the Diesel engine. The Stirling engine, whose drive mechanism does not come into contact with the combustion gases and which gets along without valves, will not require much effort for maintenance so that acceptable operating costs can be expected on that account, too.

The purchase price looks somewhat more problematical. Most of the Stirling engines with rhombic drive that were built and tested in the past are complicated and expensively built and could hardly be produced cost effectively even in large series taking advantage of all possibilities for economizing. So, in addition to research efforts for the improvement of technical data of the Stirling engine, development work must be directed towards simple engines that can be manufactured in production and economically.

Some progress has been made in this direction in the "Development Group-Stirling Engine,M.A.N.-MWM." As an example, the new concept for heater heads should be mentioned: identical straight pieces of pipe, bends and housing parts are soldered together in a one-step process to form the completed heater head, Fig. 7. The first experiments already showed how free of problems this construction is and how it promises considerable savings in production costs. Just like the heater head, a whole series of subassemblies of the Stirling engine must be further developed, like the air preheater, the combustion chamber, the piston rod gasket, the control and the drive. Some partial successes have already been achieved in these areas

as well. Particularly noteworthy is the simplification of the transmission, when changing from rhombic drive to the crosshead drive of a double-acting Stirling engine. In the double-acting engine the top of the piston in each cylinder works together with the bottom of another cylinder, with which it is connected via the heater, regenerator and radiator, Fig. 8. This cuts the number of moving parts to half, which expresses itself in considerable simplification and cost reduction of the engine. A double-acting Stirling engine, with subassemblies of new design, is now being constructed. Data for the approximate costs of production of this engine are not yet available, however.

Not only in Germany, but abroad as well, does the further development of the Stirling engine go on at an intensive pace. The effort invested in this development permits expectations that the Stirling engine will approach the goal, of being used for vehicle propulsion, much closer during the next few years.

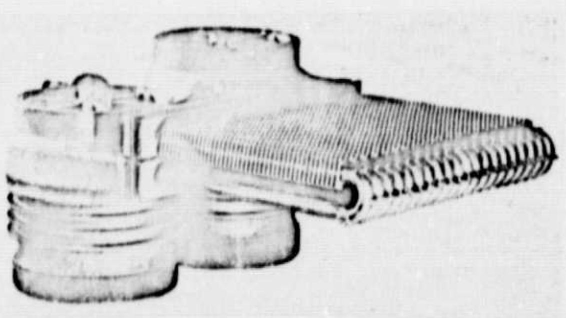

Fig. 7 New heater head for a one-cylinder Stirling engine.

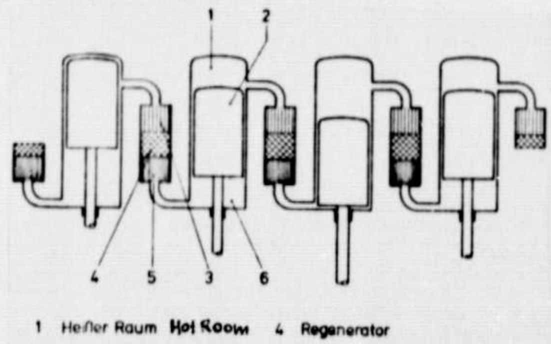

Fig. 8 Schematic of a double-acting Stirling engine.

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Discussion

/91

Dr. Th. Lin:

The Stirling engine delivers lower values of CO. That is remarkable, since the pressure in the combustion chamber is lower than in the Otto engine. Lower pressure favors the formation of CO. It leads to the question whether the relative high CO-content for the Otto engine is perhaps caused by disturbance factors and not by the law of combustion balance.

Dr.-Ing. P. Kuhlmann:

To the question about the CO-exhaust gas values it must be said that they are caused less by the pressure in the combustion system than by the air ratio during combustion. Since adequate surplus air was always available during the driving tests favorable CO-test values resulted.

Dipl. Ing. B. Herrmann:

1. The burner system is only indirectly connected with the engine characteristic. The exhaust gas values should therefore be presented as functions of the combustion chamber parameters.

2. The heater head experiences high thermal stress, hot gas (~2000°C) on the outside, hot helium on the inside (600°C). The service life of this component will be crucial for the cost effectiveness. Corrosion will present a problem similar to that for gas turbines.

Dr.-Ing. P. Kuhlmann:

The question of whether the exhaust gas values measured should not rather have been presented as function of the combustion chamber parameters is justified. The presentation in the engine performance graph was chosen to make comparison with other engines and with legal requirements easier.

It was correctly remarked that the heater head is exposed to very high thermal (but also mechanical) stress. Experiments on the Stirling engine have so far shown that the service life of the heater head is influenced more by the creep characteristics of the material than by corrosion. These experiences relate to operation with gas oil.

Dipl. Ing. R. Maly:

1. How does one accelerate with the Stirling engine when it is built into a vehicle, resp. how is mechanical work controlled?

2. What effect does this control have on the overall efficiency (travel in town, for instance)?

Dr.-Ing. P. Kuhlmann:

The output control of the Stirling engine could not be discussed during the lecture because of limited time. But questions resulting from the output control will be dealt with in the printed manuscript.

Dipl.-Phys. G. Hewig:

What are the lowest temperatures for which Stirling engines can be used, assuming one is satisfied with 5-10% efficiency? I am thinking of the use of Stirling engines for technical exploitation of solar energy.

Dr.-Ing. P. Kuhlmann:

The question about data for the Stirling engine at reduced heater temperature can be answered like this: measurements showed a decrease in efficiency to 15% (resp. 7%) for reduction of the heater temperature to 400°C (resp. 300°C). The engine was not designed for such low heater temperatures, however, which is why more favorable values may be expected for an engine optimized for such operation.

Dr. F. Gross:

How high was the gas temperature in the combustion chamber during your experiments?

Dr.-Ing. P. Kuhlmann:

Gas temperature was not measured, but according to calculation it lies between 1800°C and 1900°C in the middle of the combustion chamber.